What is the Nature of Hot Nuclear Matter?
Exploring QCD at High Energy Density

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Introduction

One of the fundamental tasks of modern Nuclear Physics is the understanding of the structure of the vacuum, and the long distance behavior of the strong interaction, one of the four basic interactions of nature. Quantum Chromodynamics (QCD) is the present theory of the strong interaction in the context of the Standard Model of particle physics. However many of the primary features of our universe are not easily understood from the form and symmetries of the Standard Model. A rather startling view of the vacuum arises when one examines the long distance behavior of QCD. The vacuum - rather than being empty – is composed of a quark condensate that fills all of space, breaking the symmetries of the Standard model and giving rise to a variety of phenomena: the confinement of quarks into hadrons, the binding of nucleons in the nucleus, and the large mass of hadrons as compared to the light quarks (see sidebar). It is a remarkable fact that a proton, made of primarily 3 light quarks, weighs about 300 times the mass of a bare quark - the majority of the mass of a proton comes from its coupling to the quark condensate which comprises the QCD vacuum.

Can the properties of the vacuum be changed experimentally? Lattice QCD calculations tell us that this is possible. At high temperature, the underlying symmetries of the Standard Model will be restored, when the vacuum melts at temperatures exceeding 170 MeV. At these temperatures matter should behave as a plasma of nearly massless quarks and gluons, known as the quark-gluon plasma (QGP), a state existing in the first few microseconds after the big bang.

The vacuum, and in fact any system of quarks and gluons, will have a complex phase structure, similar to that of many other bulk materials. One example is ordinary water, which exhibits the well-known phases of solid, liquid, and gas, together with the accompanying phase transitions. The QCD phase diagram is shown in figure 1. The phase structure of the vacuum state is along the vertical axis. There are actually two phase transitions which are related. The first is that of deconfinement, in which the quarks and gluons become free of their bondage in protons and mesons. The second is that of chiral symmetry restoration in which the masses of the quarks are reduced to their bare quark values. If the temperature were above the chiral phase transition temperature then the proton, for example, would be very light. Its mass would be a few MeV, characteristic of the light quark masses. It is still an open question as to whether these two phenomena happen under exactly the same conditions of pressure and temperature.

The completion of the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratories (BNL) ushers in a new era for studies of the most basic interactions predicted by QCD in bulk nuclear matter at temperatures and densities great enough to excite the expected phase transition to a quark-gluon plasma. As this program matures, experiments at RHIC will provide a unique window for detailed studies of the hot QCD vacuum, with opportunities for fundamental advances in the understanding of quark confinement, chiral symmetry breaking, and, very possibly, new and unexpected phenomena in the realm of nuclear matter at the highest density. By colliding heavy ions at extreme energies, mesoscopic regions of sufficient energy are created with conditions favorable for melting the normal vacuum and creating this novel state of matter. With the unique ability to collide beams of ions from protons to gold, and with center of mass energies from 20 to 100 GeV per nucleon, RHIC addresses a number of fundamental questions:

What are the properties of the QCD vacuum and its connection to the masses of the hadrons? What is the origin of chiral symmetry breaking?

Can we locate signatures of the deconfinement phase transition as the hot matter cools? What is the origin of confinement?

What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?

In Relativistic Heavy Ion Collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved?

The US has the premier laboratory in which to study these questions. It is likely that an initial understanding of high density QCD matter and its associated phase transitions will be achieved in the next several years. However there will still be a great deal to be done subsequent to the initial discoveries. Indeed, humans have known water, ice and steam for many thousands of years, but scientists are still using modern techniques to discover new properties and phases of water. Similarly, it is clear that expanded facilities will be necessary in the outlying years of this long-range plan to get a detailed description of hot nuclear matter.

Achievements Since the Last Long Range Plan

The US program in Relativistic Heavy Ion Physics has a long history, starting at the Bevalac (fixed target machine at Berkeley with ~1 GeV center-of-mass energy) and continuing to the AGS (fixed target machine at BNL with ~ 5 GeV center-of-mass energy), with a large contingent of the US community participating in the CERN-SPS program (fixed target machine with ~ 20 GeV center-of-mass energy). A new frontier has begun with the initiation of the RHIC program (colliding beams machine with ~ 200 GeV center-of-mass energy), giving us an increase in center of mass energy of almost an order of magnitude. The fixed target experiments the AGS and the CERN-SPS on one hand, and collider experiments at RHIC and the LHC (colliding breams machine at CERN with ~ 7 TeV center-of-mass energy) are studying rather different regimes on the QCD phase diagram as shown in figure 1. The fixed target experiments have studied systems where the baryon density is several times that of normal nuclear matter. In contrast, heavy ion collisions at RHIC and the LHC take us into the regime where the net baryon density of the system is very low. This situation is of course, particular interesting because it is, essentially, a high temperature vacuum. In addition, theoretical calculations, both analytical and lattice gauge calculations have improved – lattice calculations have enabled theoreticians to calculate, with more certainty, various parameters such as the phase transition temperature.

AGS and CERN programs

QCD has yielded its secrets up slowly. Even in the perturbative regime where theoretical calculations are straightforward, the physics community did not immediately accept experimental evidence for gluons. A number of expected signals of quark gluon plasma formation have been observed in fixed target experiments at CERN (and some at the AGS), but the evidence is not yet unambiguous. Some of the most important of the results from CERN and the AGS are briefly reviewed here. A more complete review can be found in Nuclear Physics: The Core of Matter, the Fuel of Stars. (by the Committee on Nuclear Physics, National Research Council, National Academy Press, 1999)

Studies of particle abundances and spectra, as well as Bose-Einstein correlations, which give information about the space-time evolution of the collision, from the AGS and CERN indicate that the system undergoes a state of rapid expansion and is close to both chemical and thermal equilibrium. Thermal equilibrium is thought to be reached very rapidly, but standard hadronic cross sections have difficulty accounting for the rapid rate at which this thermalization occurs. However, interaction cross sections arising from colored quarks and gluons are larger and could drive rapid thermalization.

A state of free quarks is expected to show a strong enhancement of strangeness, particularly of anti-strange particles, whose yield would ordinarily be suppressed by their relatively large masses. Experiments at CERN, in particular WA97 see enhanced strange anti-baryon production, with increasing enhancement for each additional unit of strangeness. Experiments at the AGS, which have been able to detect only the $\bar{\Lambda}$, see a strong enhancement in the $\bar{\Lambda}$ to $\bar{p}$ ratio (E864/E917). Thus far, standard hadronic models cannot reproduce these results.

In 1986, Matsui and Satz suggested charmonium as a probe of a deconfined medium created in relativistic heavy ion collisions. A deconfined medium would break up a $c\bar{c}$ quark pair created by hard nucleon-nucleon scatterings, thereby causing the charmonium state to “melt”. This depends on the energy density of the medium and the species of charmonium being considered, with the less tightly bound χ and ψ’ states breaking up at lower energy densities than the J/ψ. Just such a phenomenon was observed by NA50. Theoretical and experimental work was required to separate initial state effects on charmonium formation, final state breakup by ordinary hadronic matter (as observed in p-nucleus collisions, for example) and the medium effects of interest.

J/ψ suppression signals deconfinement. Signatures that may be interpreted as evidence of chiral symmetry restoration were also seen. NA45 observed an excess in electron pair yields at invariant masses between 200 and 800 MeV which can be explained as a broadening and mass shift of the ρ meson due to the onset of chiral symmetry restoration. Competing interpretations of the data as arising from thermal radiation are also possible.

The fixed target experiments have certainly proven that heavy ion collisions create high energy and baryon densities. The density of hadrons is so large, that there is simply not enough room for them to co-exist as a superposition of ordinary hadrons. The observed signatures are not readily explainable by standard hadronic models. It is also clear that a great deal remains to be done in the CERN/AGS energy regime. A new experiment (NA60) is now under construction at CERN to measure the charm production cross-section, necessary to resolve questions in interpretation of the dilepton results. Other laboratories in Japan and Germany are contemplating construction of facilities to further these studies as well. Systematic understanding of the signals, by varying the beam energy for example, were hampered by the fact relativistic heavy ion work at both CERN and the AGS shared running time with other programs. One of the critical lessons for the Relativistic Heavy Ion community in the US is that a commitment to a thorough study using a dedicated machine is imperative. A systematic measurement of multiple signatures in p-p, p-nucleus and nucleus-nucleus collisions is a prerequisite to a clear and unambiguous physics conclusion.

A major theoretical advance in a very different region of the phase diagram has been made in the understanding of cold quark matter at high density, at the far right of figure 1. In this very dense but very cold environment, quark matter displays many characteristics more familiar to a condensed matter physicist than to a plasma physicist: Cooper pairs form, and the quark matter becomes a color superconductor, characterized by Meissner effects and gaps at the quark Fermi surfaces. Cold quark matter may exist in the centers of neutron stars. We can hope that it will become possible to use astrophysical observations of neutron star phenomena to learn whether or not this is true. Ultimately, we must fit together the picture of cold dense quark matter gained from astrophysical observation with the picture of hot quark-gluon plasma that we hope to gain from experiments at RHIC into a coherent, unified phase diagram for QCD.

First glimpses from the initial run of RHIC

The Relativistic Heavy Ion Collider, RHIC, which began construction in 1991, was completed and commissioned in the summer of 2000. The first data taking run lasted for 3 months, during which the machine reached 10% of design luminosity at 130 GeV/nucleon center of mass energy in Au-Au collisions. Figure 2 shows a picture of one of these early collisions from the STAR detector. A second run of the collider started in June of 2001 and will complete in early 2002 in which it is expected that the machine will reach full the full design luminosity at an energy 200 GeV/nucleon in the center of mass for Au ions. The detectors, which were only partially instrumented for the first run, are substantially complete. All were equipped with identical zero-degree calorimeters to determine the impact parameter, or centrality, of the collision and allow selection of identical classes of events in all four detectors (see sidebar for the description of centrality). The detectors are shown in figure 3.

In the 2000 run, about 10M events were collected between the 4 detectors with RHIC operating at 65GeV per nucleon, allowing for a good start on the physics program. About 2 orders of magnitude more events are expected in 2001.Analysis of the data has taken place in a timely fashion, and already much has been learned. Prior to the start of the RHIC experiments, very little was known about collisions of heavy ions at very high energies; for instance, predictions of the number of particles emerging from a collision varied by factors of 4. What follows is a sample of the most important, early results as of the writing of this document.

The particle density in central gold-gold collisions in the hottest region, normalized to the number of participating beam nucleons, is about 70% higher than at CERN (PHOBOS, PHENIX, STAR). This means that already at 65% of RHIC's design energy, the created energy density is at least 70% higher than previously attained at CERN. In the most violent collisions more than 6000 particles are produced (PHOBOS), and for the first time in heavy ion collisions a clear central plateau is seen (PHOBOS, STAR), yielding important information on the space-time aspects of the collision and particle production process. Furthermore the yield per participant increases with centrality (PHENIX, PHOBOS) indicating the importance of multiple collisions and hard processes (figure 4). A measurement of the transverse energy distribution by the PHENIX collaboration shows a similar behavior. Depending on the thermalization time, the data imply that the energy density may be considerably higher at RHIC than at CERN.

The azimuthal asymmetry of particle production in peripheral and semi-central collisions, known as elliptic flow, is found to be surprisingly large as shown in figure 5 (STAR, PHOBOS, PHENIX). This is evidence of a high degree of thermalization early in the collision with a build up of high pressure followed by a violent explosion.

In the center of the collision, the baryon to antibaryon ratio approaches unity (STAR, BRAHMS, PHOBOS, PHENIX) indicating that the quantum numbers of the hot system are approaching that of the vacuum. Bose-Einstein correlation studies have yielded size parameters of approximately 6 fm (STAR), surprisingly similar to that measured at CERN.

One of the most intriguing results comes from a measurement of the neutral pion transverse momentum spectrum. High transverse momentum particles are expected to be leading particles from quark and gluon jet fragmentation. A fast moving colored parton (quark or gluon) is an ideal probe of hot nuclear matter (see sidebar). In normal nuclear matter, a quark would experience only a small amount of energy loss; hence a jet would essentially carry the energy imparted to the original struck parton. In a quark gluon plasma, the deconfined color fields would slow the quark down considerably ~ energy losses can be as much as 10 GeV/fm. High transverse momentum particles would be strongly suppressed in nucleus – nucleus collisions in which a QGP were formed in comparison to a pp collisions. Figure 6 shows a ratio between p^0's measured in central Au-Au collisions in PHENIX and p^0's in pp collisions scaled by the number of binary collisions. The ratio is significantly less than one. The usual nuclear "Cronin" effect is expected to enhance this ratio above one. Whether this is a definitive signal of a QGP is yet to be determined. Future data will give more statistics and higher transverse momentum, as well as proton nucleus data for comparison.

The interpretation of all these facts in terms of the temperature, entropy production, and ultimately on the existence of a phase transition will take some time. Early results on charmonium suppression, dilepton spectra, and multi-strange anti-baryons will require data to be taken during the 2001-2002 year. In any case this has been a spectacular beginning for the RHIC experiments.

Scientific Opportunities

Scientific Opportunities: the Plan

The Relativistic Heavy Ion Collider has just begun its task of uncovering the secrets of QCD. Detectors have been completed only recently, and the second run is underway. The next few years should yield a wealth of new information. *The highest priority for the Relativistic Heavy Ion community is to utilize RHIC to its fullest potential. Sufficient running time is required to realize the physics promise of RHIC and reap the rewards of our investment in RHIC's construction. Certain short-term upgrades will be necessary as well as R and D for major upgrades to the machine luminosity and to the detectors.* Further in the future, we must implement significant upgrades of the collider and experiments. Such an upgrade program to increase luminosity and add new capabilities to the experiments will allow in-depth pursuit of the most promising observables characterizing the deconfined state. Following the results of the R&D, a detailed plan and schedule can be made. A gradual start of construction funding would be anticipated around 2004/5. Finally, the CERN heavy ion program will be starting at the LHC. It will be a wise to make a modest investment of manpower and money so that some US participation can be possible.

While the general structure of QCD is now firmly established, its properties have not yet been fully understood. Many fundamental problems are still unsolved, and are at the forefront of modern theoretical physics. One of the most important tools for making progress is lattice gauge theory, which allows one to solve complex non-linear field theory problems using a computer. These are some of the most complex problems in computer science and require enormous computing power. New capabilities will be needed in order to make progress, both in terms of interpreting experimental results and fundamental theoretical understanding.

Scientific Opportunities: The Physics

The 10-15 year plan outlined above will give physicists an unprecedented chance to make specific measurements as they attempt to find answers to the basic questions posed at the beginning of this section. Some of these measurements have already begun, however others will require the higher statistics and more precision measurements afforded by the upgrade path outlined.

Thermalization and equilibration

In Relativistic Heavy Ion Collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved?

The system that physicists are able to study in the laboratory is that of highly compressed nuclear matter which expands at a rapid rate, much like to early universe shortly after the Big Bang. Many of the early questions answered by experimenters will have to do with the properties of the system created at RHIC. Some of the parameters that will be crucial to understand are - the degree of thermalization, the initial temperature or energy density, the rate of expansion, and the net baryon density. Experiments probe these questions via measurement of hadrons - single particle distributions and correlations among particles - and by detecting penetrating probes, which interact only electromagnetically and therefore escape the dense system relatively unperturbed. Theory, in the form of an understanding between models and experimental data will be crucial in understanding these measurements.

Extensive study of heavy ion collisions at lower energy at the BNL AGS and CERN SPS have shown that the analysis of the distributions and correlations of soft hadrons yield the temperature and dynamics at the time the hadrons cease to interact, or “freeze out”. The space-time evolution thus measured is crucial to understanding the collision dynamics and to lending confidence in back-extrapolations to the early, hottest, phase of the collision. Systematic study of the conditions under which the hadrons freeze out, as a function of initial temperature and collision volume, will help us separate signatures of new physics from the underlying hadronic processes.

Momentum and flavor distributions of the hadrons provide information on the degree of thermal and chemical equilibration when the colliding system becomes dilute enough that hadronic strong interactions cease. Combined with other experimental information such as thermal radiation, the space-time evolution of the entire collision can be inferred. An important goal at RHIC is to determine whether equilibration occurs early in the collision, or only later, in the cooler hadronic phase. Combining hadronic observables, collective behavior reflecting early conditions, and thermal emission of virtual and real photons is possible with the suite of experiments at RHIC.

Early results from RHIC on some of these topics have already been published which indicate that the system freezes out at a lower baryon density and somewhat higher temperature than at the SPS or AGS. This is to be expected since the freeze out temperature is a characteristic of QCD and not of particular system that is being studied. As mentioned previously, flow measurements indicate that the degree of thermalization is high; hence the concepts of temperature and pressure have meaning in the system under study. More information will be coming as physicists refine their measurements.

Real and virtual photons from quark-anti-quark annihilation, materializing as electron or muon pairs are radiated from the hot, dense QCD matter. While such radiation is emitted at all times during the collision, the reaction dynamics favors emission from the hottest part of the colliding system. Thus, measurement of the distribution of the blackbody thermal radiation will yield the initial temperature. The background to such a signal is formidable since photons and electrons are copiously produced from other sources such as p^0 decay. Upgraded detectors designed to reject such backgrounds will be necessary. Systematic analysis, and variation of the initial conditions will be required to solidify the interpretation.

Deconfinement

Can we locate signatures of the deconfinement phase transition as the hot matter cools? What is the origin of confinement?

The fundamental degrees of freedom in QCD are quarks and gluons. However, free quarks and gluons have never been observed, and the physical spectrum of particles contains only “hadrons”—color singlet bound states of quarks, antiquarks, and gluons. As mentioned previously, this property of QCD has been named “confinement”; the origin of this phenomenon is linked to the properties of the vacuum. Heavy ion collisions create a hot and dense environment in which the vacuum structure can “melt”, leading to novel forms of QCD matter where quarks and gluons are no longer confined, i.e. the QGP. This kind of behavior has been confirmed by numerical calculations on the space-time lattice. Further progress in the theory is imperative, and includes both new analytical methods and large—scale numerical simulations on the lattice. New lattice methods and more powerful computers would enable a breakthrough in the understanding of confinement. To investigate the consequences of deconfinement phase transitions for the experimental observables in heavy ion collisions, we will need the development of QCD based event generators and the facilities for large-scale numerical simulations.

One of the signatures of deconfinement is the suppression of high momentum particles. Measurement of the hard scattering processes via high transverse momentum hadrons and heavy flavor distributions will indicate to what extent the fast particles lose energy in the dense medium. This energy loss results in energy transfer from fast particles to the medium and drives thermalization. Furthermore, this energy transfer multiplies the number of gluons and therefore drives particle production, increasing the density of the medium further. In fact, some theoretical predictions indicate that matter may reach the stage of gluon saturation – in such a case the physics is determined by interactions in a dense gluon gas, calculable using perturbative QCD, with subsequent hydrodynamic expansion. Measured particle yields, spectra and correlations to transverse momenta of at least 10 GeV/c transverse momentum are needed to see whether such predictions are correct. Particles with extremely high momenta will never thermalize, providing a built-in control measurement; the hadron spectra and correlations among fast hadrons will indicate at which point this becomes true. As mentioned, PHENIX may have already seen hints of this phenomenon in the p^0 transverse momentum spectra. Further measurements will be made in the second year of data taking, giving the possibility of measuring the spectrum to a transverse momentum of 10 GeV. In addition, important comparison data will be taken in the coming years in pp and pA collisions. Significant beam time is imperative for these measurements.

In the future when a luminosity upgrade is available, measurements of direct photons produced opposite high transverse momentum hadrons can be made. Since the photon recoils against the quark jet, and since it does not suffer energy loss in the deconfined medium, the photon serves as a indicator of the initial transverse momentum of the jet. This will provide a means to make careful, quantitative measurements of the energy loss. One interesting possibility is to flavor tag the high transverse momentum hadron. A leading K^- with no valence quarks is more likely to come from a gluon jet. This would allow one to measure the difference in the energy loss between gluon and quark jets. Gluon jets are expected to loose energy at twice the rate of quark jets in a deconfined medium. Later in the decade, the LHC will be able to make similar measurements at 30 times the center of mass energy, where the lifetime of the QGP is expected to be several times longer than at RHIC.

J/ψ suppression is another well-known signature of deconfinement. PHENIX will be able to measure J/y production in both the muon and electron channels. STAR will have access to the electron channel within the next several years as their electromagnetic calorimeter is completed providing a second measurement of this signature. This is a critical check between experiments, which was not done in the CERN experiments. One of the critical measurements that must accompany the measurement of the J/y is that of open charm production. To do this, specialized vertex detectors must be added with the position resolution that would allow a measurement of the charm vertex separated from the original event vertex. STAR, PHOBOS and PHENIX have all embarked on R and D programs to construct such an upgrade.

The J/y is but one of the vector mesons in the charm family. The excited states of the J/y as well as the U family will all exhibit some degree of suppression. The suppression of the associated states, c_c and c_b can also be observed since they decay to the detectable vector mesons. Each of these states will "melt" at a different temperature. In fact the U will be used as a control since it should not be suppressed at all at RHIC energies. By varying the temperature of the system though changes in beam energy and species, one can change the pattern of suppression of the various states. Not only would this be a convincing signature of a phase transition, it would give a good measure of the actual energy density. This will require a major upgrade in luminosity. In addition, when the LHC begins heavy ion operation, the U family will be detected at high rates and will be easy to analyze.

Chiral Symmetry Restoration, the Vacuum and Mass

What are the properties of QCD vacuum? What is the origin of chiral symmetry breaking and what it its connection to the masses of the hadrons?

Chiral symmetry is the symmetry between "left" and "right" handed objects and has to do with whether the direction of spin is clockwise or counter-clockwise (see sidebar).

Chiral symmetry is broken through the creation of a vacuum scalar condensate that couples to hadrons and provides most of their mass. The challenge for RHIC experiments is to search for evidence of in-medium mass changes of the low mass vector mesons associated with the restoration of chiral symmetry. A direct measurement of the mass of light vector mesons such as the ρ,ω, and ϕ is possible since they decay rather rapidly within the fireball created at the time of collisions and before hadronization.. The decay to di-electrons is particularly interesting since electrons should not be rescattered in the medium and their invariant mass should reflect the mass of the vector meson in the altered vacuum state. Since some fraction of the vector mesons decay outside the medium (in the case of the ω some 70-80% decay outside the medium), these can be used as a calibration point for the measurement. The fraction exhibiting a shifted mass should change as a function of the transverse momentum and the size of the central fireball. This would be a particularly dramatic signature of the altered vacuum. As in the case of the thermal di-electron signal, a major upgrade will be needed to reject background for detection of the ρ, the shortest lived, and hence the broadest of the vector mesons. Observation of the ρ will be important, since it decays entirely within the fireball and its spectrum may be able to give us a thermal history of the evolution of the system.

The presence of a phase transition as the system cools is also expected to cause fluctuations, which may survive the hadronic phase as fluctuations in particle number and type. Fluctuations and droplet formation are of particular interest, since similar processes may account for much of the large scale structure of the universe and the inhomogeneities observed in the cosmic microwave background. A variety of fluctuations have been proposed as a signature of a phase transition. If the transition is first order, the growth of hadronic droplets and the shrinking of quark-gluon droplets may yield a lumpy final state and large fluctuations in particle number . If the transition is a smooth but sufficiently rapid crossover, domains of misaligned chiral condensate may be formed. If the transition occurs near a critical point separating first order behavior from crossover behavior, long wavelength fluctuations imprint unique signatures on the momenta of soft pions. Experiments will search for such phenomena, and correlate their appearance with other quark-gluon plasma signatures.

The theory of chiral symmetry breaking and restoration is under active development Further theoretical progress is needed to understand the microscopic origin of chiral symmetry breaking and the mechanism of its restoration. It will include development of new analytical tools, and further progress in lattice calculations. In order to investigate chiral symmetry on the lattice, one has to be able to perform calculations with realistically small masses of quarks. This places severe constraints on the size of the lattice, and requires new methods (e.g., “domain wall fermions”), and new and more powerful computers.

The Strong CP problem

While QCD allows for a violation of parity and charge conjugation combined with parity (CP), this violation has been never observed experimentally in normal conditions. This is still an active subject of theoretical study. It would be of great interest to check if CP violating processes are possible under extreme conditions of high temperature and density. Theoretical progress here is linked to the understanding of topological effects in gauge theories at zero and finite temperatures. This requires both analytical tools and lattice simulations. To search for the effects of anomalous parity and CP violation in experiment, one needs to incorporate these processes into the event generators.

Clever experimental signatures for CP violating bulk phenomena in heavy ion collisions at RHIC have been devised. In theory, since CP is conserved in ordinary strong interactions, the signature of the altered CP state should shine through the hadronic debris.

High Density Matter

What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?

Gluonic interactions may be expected to dominate the first few fm/c of RHIC collisions, immediately following the initial nucleon-nucleon interactions as the nuclei penetrate one another. Gluon fusion processes dominate the production of charm and bottom quarks, as well as drive W production at energies attainable at RHIC. Consequently, measurements of open charm and bottom decays will likely be the most important ways to study the gluon fields inside heavy nuclei and their excitations in heavy ion collisions. Of particular interest are distributions at low-x, where x is a measure of the momentum fraction of a nucleon carried by an individual quark or gluon. The Drell-Yan process of quark-antiquark annihilation probes the quark structure functions. Achieving adequate luminosity and detector acceptance to measure this at RHIC will be an invaluable tool to study the evolution of the quark structure functions to small-x inside heavy nuclei (measurements of p-nucleus collisions will yield this information), as the parton distributions evolve during a heavy ion collision.

Nuclear shadowing will be measured directly via Drell-Yan and other hard processes in proton-nucleus collisions. Experiments must measure, with sufficient statistics, the dimuon distributions at high mass and hadron spectra at high transverse momentum (at or above 10 GeV/c) to determine the extent of shadowing in kinematic regions accessible at RHIC. The answers feed back, of course, into understanding the initial conditions in nucleus-nucleus collisions. However, they also probe the gluon field properties directly. If the gluon and quark densities can saturate, this will affect the gluon distribution deep inside a heavy nucleus as well as the dynamics of the early stage of a heavy ion collision. Measuring the intrinsic transverse momentum of the quarks within the nucleon via hard probes, and observing how this depends on x as well as the volume of dense matter, can address these questions. Such measurements will require increased luminosity for sufficient yields. They will also require upgrades of the detectors for efficient reconstruction of the hard probes. The LHC should have excellent capabilities to study this physics as well, since the apparent density of low-x virtual gluons will almost certainly be at saturation.

Theoretically, the behavior of QCD at the high-energy frontier has not yet been understood. The most simple, and most fundamental, questions are still unanswered: Why do hadron cross-sections rise? How are particles produced? What is the wave function of a high-energy hadron? RHIC will help to find the answers by providing detailed data on particle production in a wide range of atomic numbers and energies. Progress in the understanding of high-energy behavior in QCD will allow us to reconstruct initial conditions in heavy ion collisions, a crucial prerequisite for theoretical description of the entire process. It will also need further development of theoretical tools, where there has been a remarkable recent progress as well as large-scale real-time Monte Carlo numerical simulations.

Correlating the signatures

Phase transitions occur at a particular energy density. It is crucial to cross correlate the conditions under which the signals appear in order to rule out proposed hadronic explanations and prove that new physics is the only consistent explanation. This necessitates experiments measuring multiple signatures, with sufficient statistics, a good systematic understanding, and good cross checking of event classes across different experiments. Finally, enough data must be taken looking for these same observables in proton-proton and proton nucleus collusions in which a phase transition is not expected to occur to provide a baseline for the nucleus-nucleus measurements.

Figure Captions

1) **Phase diagram**

The QCD phase diagram showing temperature on the abscissa, and baryon density on the ordinate. The green band indicates the range of temperatures and baryon density in which a phase transition (both chiral and deconfinement) is thought to occur. The region indicated near the y-axis describes the vacuum, with a zero net baryon density. The trajectory followed by the systems created at the AGS and SPS with approximately 4 to 20 GeV CM energy, and RHIC with a 200 GeV CM energy are shown. The region of cold, high-density superconducting matter is shown to the far right.

2) **STAR event**

A central Au-Au at event as seen in the STAR detector at RHIC. The side view and end view of the Time Projection chambers are shown. Each colored radial line emanating from the center corresponds to a track produced in the collision. A central Au-Au collision has typically 6000 particles.

3) **The 4 RHIC detectors**

STAR is a large acceptance detector built around a central Time Projection Chamber (TPC) in a solenoidal magnetic field. Inside the TPC is a silicon vertex tracker (SVT) for detecting secondary vertices. An electromagnetic calorimeter (EMCAL) and forward TPC's are being installed in the next few years. A small acceptance RICH detector for high momentum particle ID will be replaced in the next several years by a TOF system.

The PHENIX detector is composed of 4 spectrometers optimized for detecting and identifying electrons, muons, photons and hadrons. Multiple detector subsystems are used in the two central arms, yielding good momentum resolution and particle identification. Of particular note is redundancy in electron identification capabilities, giving a total e/π rejection of better than 10^{-4}. Excellent hadron identification via time-of-flight (TOF) is available over a small angular range. Muons are detected in two arms covering forward and backward angles, where the muons have a kinematic boost enabling them to be separated from the copious hadrons produced in the collisions.

PHOBOS, one of the two smaller detectors, is primarily composed of silicon and is optimized for large event rates. It consists of a central two-arm spectrometer, allowing for measurements at very low transverse momentum, and a full acceptance multiplicity array. High transverse momentum particle identification is provided by a TOF system.

BRAHMS specializes in measuring the fragmentation region of the collisions. It is composed of two spectrometers, each with a rather small aperture, which rotate thereby giving a large angular coverage by combining data from runs with the detectors in various positions.

4) dN/deta

A plot showing the multiplicity density normalized to the number of incoming nucleons for various energies in Au-Au collisions as compared to $\bar{p}p$ collisions, showing that the yield in heavy ion collisions is higher than one would expect when scaling from simpler systems. The points from the PHOBOS detector at RHIC are solid circles with the errors indicated by the open rectangle at center of mass energies of 56, 130, and 200 GeV. The line passing through the $\bar{p}p$ points is an interpolation of the data to guide the eye. The dotted line and solid bold line are various models for heavy ion collisions.

5) Flow

Elliptic flow (solid points) as a function of centrality defined as n_{ch}/n_{max} from the STAR collaboration. The open rectangles show a range of values as expected for v_2 in the hydrodynamic limit, scaled from ϵ, the initial space eccentricity of the overlap region. The lower edges correspond to ϵ multiplied by 0.19 and the upper edges to ϵ multiplied by 0.25.

6) π^0 jet suppression

A high transverse momentum particle comes primarily from the leading particle of a jet. As such it reflects the jet energy. Jets are produced from hard collisions between quarks and gluons early in the collisions between high energy protons or nuclei. If a quark-gluon plasma were formed in a heavy ion collisions, jets would loose energy as they leave the collision region. This would produce a deficit of high transverse mometum particles in heavy ion collisions (where one might be forming a QGP) relative to pp collisions (where one probably does not form a QGP). High transverse momentum π^0's, measured by the PHENIX detector are shown in figure (a) for both central and peripheral collisions. The peripheral collisions should behave similarly to pp collisions, and indeed one sees that the peripheral data match the pp data correctly scaled for the fact that several nucleons are involved in peripheral Au-Au collisions (lower line). The central data, however, show a marked deficit from expectation. Figure (b) makes this more dramatic by dividing central data by the peripheral data, scaled appropriately with the number of binary collisions. Naively, one would expect that this would yield a flat line at 1, while the data is significantly below this level. Systematic errors for the p^0 measurement, and the scaling are shown. Expected effects such as shadowing and the "Cronin" initial state multiple scattering would enhance this ratio, while PHENIX observes a deficit.

Sidebar Pages

1) What is chiral symmetry and what is its connection to mass and the vacuum?

Chiral symmetry is the symmetry between right and left-handed objects. In ancient China, a warrior would cut off the left ear of his victim to keep count of the number of people he had killed. He could not cheat because a left ear is unique - there is no way a right ear can be turned into a left ear. Of course, this system would have worked just as well if they has decided to use right ears instead of left - this reflects fact that our bodies, at least generally, are left-right symmetric. Physicists deeply believe that the universe is left-right – that is chirally - symmetric. The handedness of a particle is defined by the direction of the spin relative to the direction of velocity. If one looks along the direction of travel of a particle, a clockwise direction of spin is defined as right handed; a counter-clockwise direction is defined as left-handed (see figure sidebar1 figure1). The bad thing about this definition is that one can do a transformation of the coordinate system and change the definition of the spin, even though we really didn't alter the intrinsic characteristics of the particle at all. Imagine an observer on a rocket going very fast - faster than the motion of the particle. He would see the particle moving in the opposite direction and would believe the particle was left-handed.

In this case we could change a right-left symmetric universe where half the particles were left handed, and the other half was right handed, into a universe in which all particles were right handed if we had a very fast rocket ship. This would then spoil the left-right (chiral) symmetry. How might we avoid this situation and preserve chiral symmetry? Einstein taught us that nothing can move fast than the speed of light. Massless particles all move at the speed of light. If a particle were massless, than we could not move fast enough to change its direction; its handedness is preserved. If the universe is really chirally symmetric, then particles must be intrinsically masses. But of course, this doesn't match the universe that we see. Where then does mass come from?

Physicists believe that particles are, in their basic nature massless, and that they acquire mass through their interactions with the vacuum. This is the process of chiral symmetry breaking. QCD has the property that the lowest energy state is not empty space, but rather is a vacuum filled with a condensate, which is itself composed of quarks as shown in figure (sidebar1 figure 2). In turn the interactions of quarks with this quark condensate conspire to make the quarks behave as if they have mass.

This state of the universe is dependent on the temperature. If the temperature is high, as in the early universe, or in a relativistic heavy ion collision, the vacuum state changes and the quarks will exhibit their massless nature.

Although this may seem a bit contrived, and seems to contradict our natural belief that space is empty, this is what scientists believe, and forms a integral part of the standard model of particle physics. Relativistic Heavy Ion Collisions open up the possibility of observing the effects of the vacuum directly, by heating it up and changing its characteristics – i.e. by melting the vacuum.

Sidebar 1 Figure 1)
Chirality
The chirality, or handedness of a particle is defined as the direction of the spin when viewed along the direction of motion. In figure (1a) the particle moves to the right. If we view it from behind, it appears to be spinning clockwise, and hence we would define this as right handed. However to an observer on a rocket moving faster than the particle (1b), the direction of motion appears to be towards the left of the picture as in figure (1c). To a person on a rocket ship, looking along the direction of particle motion, in this case toward the left of the page, the particle would appear be spinning counter-clockwise, that is would be left-handed. We can preserve chiral symmetry only if we prevent anything moving faster than our particle. This can be done if the particle is moving at the speed of light, which is possible only if the particle is massless.

Sidebar 1 Figure 2)
The Action Density of the QCD vacuum. All space is filled with the QCD condensate depicted in this picture. The interaction of particles with this background condensate gives rise to most of the mass that makes up our earth (hadronic matter). This depiction of the energy density of the QCD vacuum was done on the CSSM supercomputer at the University of Adelaide

Courtesy of D.B. Leinweber, CSSM, University of Adelaide.

2) Relativistic heavy ion collisions and jet suppression

Anatomy of the collision (Sidebar 2 figure 1)
Relativistic Heavy Ion Collisions such as those produced by RHIC, the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory on Long Island, New York, provide physicists a chance to study very hot dense matter similar to that which existed a few micro-seconds after the Big Bang. In a typical gold-gold collision, when viewed in

the laboratory frame, the two nuclei initially appear a flat pancakes - a result of Lorentz contraction. In the early pre-equilibrium phase, many hard collisions occur between the quarks and gluons producing thousands of other quarks and gluons in an enormous cascade. The next stage of the collision is the one of primary interest. These secondary quarks and gluons equilibrate into a hot cauldron of matter - the quark-gluon plasma. Because of the low baryon number this plasma is essentially a high temperature vacuum. In the final stages the plasma cools and condenses into ordinary particles which are then seen by the detectors,

Defining the geometry (Sidebar 2 figure 2)
Head on "central" collisions, are the most violent with the most “participants” and produce the largest volume of hot matter. More glancing "peripheral" collisions will have little, if any hot matter. These peripheral collisions are particularly important since they can be used for comparison. The centrality of the collision can be monitored by detecting the cold "spectator" material as shown in the figure.

Probing the plasma (Sidebar 2 figure 3)
How can one see if a plasma is made? One of the probes that can be used to study the hot matter created are high momentum particles. In the pre-equilibrium phase of the collision, some of the quarks acquire a very large momentum which appear as jets of particles. About 1/2 of the energy is carried by a single leading particle which then gives physicists information about the momentum of the original quark as it left the collision region before fragmenting into the particles which comprise the jet. Fast quarks can traverse a region of ordinary hadronic matter with little hindrance (sidebar 2 figure 3a), however, if the central hot region were a quark-gluon plasma, the fast quark would loose a great deal of energy and the momentum of the leading particle would be greatly reduced (sidebar 2 figure 3b). This leads to a softening of the momentum spectrum. As mentioned in the main text – this is what is seen by PHENIX (figure 6). While it is yet too early for physicists to conclude that a quark-gluon plasma has been formed, it is one of the leading indications of this and signifies a spectacular beginning to the RHIC scientific program.

Sidebar 2 figure 1)
The anatomy of a collision as explained in the text.

Sidebar 2 figure 2)
Not all collisions are head on or “central” collisions. Some collisions are more glancing or “peripheral”. The centrality of a collision can be determined experimentally by measuring the number of “spectator” particles.

Sidebar 2 figure 3)
(a) Jets come from high momentum quarks that fragment into particles after they leave the collision region. If no quark gluon plasma is formed, the quark passes though nuclear matter with little resistance. (b) High momentum quarks will loose a great deal of their initial energy if they pass through quark-gluon plasma. The particles from jet fragmentation, which can be detected, will have considerably less momentum.